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Exposure dating outwash gravels to determine the age of the greatest Patagonian glaciations

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ABSTRACT

The relict moraines in Argentine Patagonia archive major expansions of the Patagonian Ice Sheet throughout the Quaternary, and are one of the few terrestrial climate proxies in the middle latitudes of the Southern Hemisphere that extends beyond the last glacial cycle. Determining their individual ages has proved challenging but has important implications for our understanding of terrestrial climate change in southern South America over the duration of the Quaternary. Here, for the first time, we demonstrate that sediment on outwash terraces can be directly dated to determine the timing of Early-Middle Quaternary glacial advances in southern South America. Cosmogenic ^{10}Be and ^{26}Al surface exposure ages were obtained from outwash gravels associated with two of the oldest glacial sequences in the Lago Pueyrredón valley, 47.5º S, Argentina. The outermost 'Gorra de Poivre' glacial sequence marks the greatest extent of the Patagonian Ice Sheet. A cobble from this surface gives ^{10}Be and ^{26}Al surface exposure ages of ca. 1.2 Ma, which are consistent with bracketing ^{40}Ar/^{39}Ar age constraints obtained elsewhere in Patagonia. This is the first time Early Pleistocene glacial surfaces have been directly dated in Patagonia. Cobbles on a younger 'Cañadon de Caracoles' outwash terrace give exposure ages of ca. 600 ka, while four of five boulders on an associated moraine give exposure ages that are significantly younger. If the demonstrated stability of outwash terraces in the valley is common throughout the region, it will be possible to extend Patagonian glacial chronologies as far back as the Early Pleistocene.

Keywords: *Glacial chronology, southern South America, Marine Isotope Stage 16, cosmogenic nuclide surface exposure age dating, beryllium-10, aluminium-26*

INTRODUCTION

Southern South America contains what has been described as '…probably the most complete and intact sequence of Quaternary moraines anywhere in the world' (Clapperton, 1993; p.358). The relict moraines in Argentine Patagonia archive major expansions of the Patagonian Ice Sheet over more than one million years (Mercer, 1976). This unique glacial geologic record offers rare insight into long-term terrestrial climates at a key mid-latitude position in the dominantly oceanic Southern Hemisphere. Establish the timing of Quaternary glacial advances in the region would provide significant insight into how the regional climate signal has developed alongside global trends as revealed by ice sheet and ocean sediment cores. This has important implications for our understanding of terrestrial climate change in Southern South America over the duration of the Quaternary. However, exploiting this unique record requires accurate age determinations for the glacial sequences on timescales greater than 10^5 a.

Tills that pre-date the Last Glacial Maximum in Patagonia are in places bracketed in age by $^{40}Ar/^{39}Ar$ and K-Ar ages on interbedded lava flows (e.g., Meglioli, 1992; Mercer, 1976; Singer *et al.*, 2004), by maximum radiocarbon ages (McCulloch *et al.*, 2005), by paleomagnetic measurements (Sylwan *et al.*, 1991), and more recently by cosmogenic-nuclide surface exposure ages (Kaplan *et al.*, 2005). The latter technique offers the potential to provide direct ages for the glacial landforms and does not rely on rare geologic associations with dateable material. However, the common approach of targeting surface boulders is problematic on older moraines (>10^5 a) because erosion causes these steep-sided, unconsolidated landforms to lower and become blurred in the landscape through time (Putkonen and O'Neal, 2006). Because the moraine surfaces are renewed with lowering, exposure ages can be reduced to minimum limiting ages.

Hein *et al.* (2009) demonstrate that with favorable environmental conditions, the outwash terraces associated with the moraines are stable and can yield accurate surface exposure ages for deposition up to at least ~260 ka. This is principally because flat surfaces are less susceptible to gravity driven diffusion. In the Lago Pueyrredón valley (Fig. 1), a ^{10}Be concentration depth-profile in the Hatcher outwash sediment indicates negligible inheritance and an age of ~260 ka. Cobbles on the terrace surface have ages of 190 – 265 ka; this range in ages reflects disturbance in continuous exposure. The geologic processes causing this (bio-, cryo-turbation, exhumation, burial) become increasingly important on older surfaces. Therefore, the feasibility of dating the oldest glacial sequences in Patagonia by this method is unknown and is something we address explicitly here.

In this study, we date outwash sediment from the two stratigraphically oldest glacial sequences in the same valley and compare this to independently dated records from elsewhere in Patagonia. In doing so, we critically evaluate the long-term stability of the outwash terrace and its suitability as a target for surface exposure age dating of Early Pleistocene events.

STUDY AREA

The Lago Pueyrredón valley (Fig. 1) has been repeatedly occupied by a major outlet glacier of the Patagonian Ice Sheet as evidenced by at least four distinct moraine sequences separated by ~100 m escarpments that rise toward the east (Caldenius, 1932). Clear ridges are visible on the oldest moraines, and braided meltwater channels occur on some outwash terraces. The latter indicate original surface morphology and long-term stability because outwash terraces become isolated after deposition when, during interglacials, a reverse in drainage direction occurs and the area drains to the Pacific rather than to the Atlantic.

We sampled from two outwash terraces associated with the Gorra de Poivre and Cañadón de Caracoles glacial sequences. The Gorra de Poivre moraine system is the local expression of Mercer's (1976) 'Greatest Patagonian Glaciation' (GPG), the most extensive ice advance in Patagonia (Coronato *et al.*, 2004). The $^{40}Ar/^{39}Ar$ ages that bracket the timing of the GPG are separated geographically (Fig. 1a), but the deposits are regarded as contiguous, based on geologic mapping (e.g., Caldenius, 1932; Coronato et al., 2004; Mercer, 1976; Rabassa, 2008; Singer et al., 2004; Ton-That et al., 1999). On the eastern margin of the valley, the moraines are characterized by a series of broad, low relief ridges (~20 m) with gentle slopes (<5°) and with few surface boulders. The associated outwash terrace dips eastward at ca. 0.4° and is sparsely vegetated with sediment ranging from coarse sands to cobbles. There is some evidence for sediment turning; cobbles are often ventifacted on all sides, and several are oriented with their long-axis perpendicular to the terrace surface; an observation common to permafrost soils (Washburn, 1980).

On the basis of previous studies, the less-extensive Cañadón de Caracoles moraine system is older than 260 ka and may be older than 780 ka, the latter age is based on reversely magnetized glacial sediment associated with the outermost Cañadón de Caracoles ice limit (Fig. 1b) (Hein *et al.*, 2009; Sylwan *et al.*, 1991). The system may mark more than one glaciation; relief between moraine crests exceeds 200 m and outwash channels cross-cut more distal glacial deposits. The moraines sampled in this study, located intermediate to the outer and innermost moraines of this sequence, are relatively continuous and sharp crested (5-10 m crest-width) with slopes of ca. 8º and 12º and relief of ca. 20 and 50 meters on the ice-distal and ice-proximal sides, respectively. Moraine boulders are abundant and often show signs of minor surface erosion such as flaking (<2 cm) and ventifacts. The associated outwash terrace is 1.5 km wide and can be traced for 11 km as it dips (0.5º) toward the east. Braided meltwater channels (ca. 40 cm relief) indicate limited inflation or deflation of the terrace surface since deposition. The surface is sparsely vegetated and is composed of coarse sands with a high density of cobbles and small boulders (10 – 30 cm diameter). Soils are poorly developed and in the top 10 cm only. Ventifacts are exhibited on surface clasts but restricted to exposed surfaces.

METHODS

Using an approach detailed elsewhere (Hein *et al.*, 2009), we targeted for exposure dating individual cobbles of resistant lithologies (e.g., vein quartz) from well-preserved outwash surfaces (Fig. 1b). Their preserved fluvial forms constrain total rock surface erosion, which is usually small or negligible. The semi-arid conditions and strong winds in the valley (Prohaska, 1976) play a role in minimizing post-depositional shielding from cosmic radiation (e.g., by snow), but also in eroding rock surfaces when, periodically, they entrain sand and dust particles from active outwash surfaces (Hein *et al.*, 2009). We targeted cobbles with ventifacts and interpret these features as indicating long surface exposure.

We assume that ^{10}Be and ^{26}Al inherited from previous exposure is negligible; this has already been demonstrated for the Hatcher and Río Blanco outwash (Hein *et al.*, 2009) and the sediments share the same genesis and source areas > 75 km distant. Because geologic processes tend to reduce the cosmogenic-nuclide inventories leading to young apparent exposure ages (Phillips *et al.*, 1990), we regard the oldest exposure ages as the best estimate of the deposition age (cf., Zreda *et al.*, 1994). Full sample details including photographs, descriptions, chemistry and information relevant to calculating the exposure ages are provided in the GSA Data Repository[1].

RESULTS AND DISCUSSION

The ^{10}Be exposure ages and ^{26}Al/^{10}Be ratios are illustrated in Figure 2; the corresponding data are provided in Tables DR1 and DR2 of the Data Repository, along with supplementary discussions. Exposure ages assume no rock surface erosion. Uncertainties are 1σ. Analytical uncertainties are used in the data discussion. External uncertainties include those associated with the production and scaling of cosmogenic-nuclides. The ‘scatter’ in exposure ages is derived by dividing the youngest age by the oldest age from each group.

The Gorra de Poivre outwash terrace cobbles give highly scattered (77%) ^{10}Be exposure ages that range between 278 ka and 1211 ka (Fig. 2a). The ^{26}Al/^{10}Be ratios provide no evidence of prolonged post-depositional burial (Fig. 2b). Two of the four samples give ages consistent with the ^{40}Ar/^{39}Ar ages that bracket the timing of the GPG (Figs. 1, 2a). Specifically, their ages (999 ± 28 ka and 1211 ± 36 ka) are consistent with the age of the Arroyo Telken flow (1016 ± 10 ka), which surrounds and overlies a morphostratigraphically equivalent till ~25 km to the north, and with the Bella Vista flow (1168 ± 14 ka) which underlies the most extensive tills in southern Patagonia (see Coronato *et al.*, 2004; Rabassa, 2008; Singer *et al.*, 2004). The consistency is remarkable when considering the field evidence for sediment turning, which could have reduced the samples’ exposure time. Overall, and in line with our observation of preserved moraine ridges, the result suggests long-term landform stability in the region and it further corroborates our approach to dating these surfaces. We take the oldest ^{10}Be exposure age to best approximate the timing of the GPG in the valley at 1,211 ± 36 ka (± 200 ka external).

The other two cobbles from the Gorra de Poivre terrace surface give significantly younger ages. These were oriented with their long-axis perpendicular to the terrace surface and, in contrast to the older samples, they had no ventifacts on their bottom sides. Based on our field observations, we argue these cobbles were initially shielded from cosmic radiation and later were exhumed by soil activity related to permafrost (e.g., cryoturbation) from an approximate minimum depth of 75 cm. The temperature depression during the Last Glacial Maximum was sufficient for the development of permafrost throughout much of Argentine Patagonia (Trombotto, 2008).

The four Cañadón de Caracoles outwash terrace cobbles give ^{10}Be exposure ages that range between 452 ka and 600 ka (Fig. 2a). The ^{26}Al/^{10}Be ratios provide no evidence of prolonged post-depositional burial (Fig. 2b). The top surface of the youngest cobble was severely eroded; thus the young age may have resulted from erosive mass-loss. Excluding this age, the remaining data have a scatter of 15%. The observed remaining scatter likely reflects similar localized processes inferred for the (younger) Hatcher outwash terrace, such as minor deflation of the surface causing the gradual exhumation of cobbles (Hein *et al.*, 2009). Total erosion of the oldest sample was negligible; its glaciofluvial form was preserved with only minor ventifacts of less than a few millimeters. Given this and the geologic evidence for stability of the terrace surface, together with the rather tight cluster of outwash cobble ages, we argue the oldest cobble provides a close minimum age constraint for the glacial advance at 600 ± 20 ka (± 85 ka external).

For comparison, five boulders on moraines associated with the terrace were measured. These give highly scattered (75%) ^{10}Be exposure ages that range between 148 ka and 595 ka (Fig. 2a). The oldest boulder agrees with the oldest outwash age, but is an apparent outlier within this population (3σ). The four younger boulders range in age from 148 – 265 ka and their ages increase by 22% and 59%, respectively, if a correction for erosion is applied (1.4 mm ka^{-1}; Kaplan et al., 2005). However, the young boulders have only minor signs of flaking and aeolian erosion, and even with an erosion correction, the boulder ages are younger and more scattered than the equivalent outwash cobble ages. The $^{26}Al/^{10}Be$ ratios do not support prolonged post-depositional burial as an explanation for the age discrepancy (Fig. 2b). Thus, degradation of the moraine most likely led to their recent exhumation and young apparent exposure ages; a pattern observed on the Hatcher moraines. In contrast, the oldest boulder may have remained exposed on the surface of the moraine.

In summary, our results indicate that sediment on outwash terraces can be directly dated by surface exposure methods to determine the timing of ancient glaciations. Where geologic evidence indicates stability (e.g., preserved braided-channels, imbricated sediment, ventifacts on exposed rock-surfaces only), the outwash ages are rather tightly clustered, and suggesting accurate age determinations can be obtained from these surfaces. It is encouraging to note, however, that despite the observed evidence for sediment turning on the oldest surface, two of the ages still agree with the limiting $^{40}Ar/^{39}Ar$ ages. Thus, it appears that good age constraints can still be obtained from these less-ideal outwash surfaces. The accuracy of the age determinations can be improved, however, by increasing the density of sampling and, where possible, by pairing depth-profiles within the terrace sediment to gain added insight on the age, erosion rate, nuclide inheritance and stability of the terrace sediment. At present, the rather large external uncertainties preclude linking the glacial sequences to specific marine isotope stages earlier than the Middle Pleistocene (see Fig. 3). However, with time, as further geologic calibration sites are found, these external uncertainties should reduce. Finally, our results provide additional field-evidence to indicate that on average, exposure ages from boulders on old moraines underestimate the deposition age, sometimes dramatically, even in a setting where degradation rates are generally low (e.g., Hein *et al.*, 2009; Kaplan *et al.*, 2005; Putkonen and O'Neal, 2006; Zreda *et al.*, 1994). If the demonstrated stability of outwash gravels is common throughout arid Patagonia, it should be possible to reconstruct the timing of glacial advances in other outlet valleys where currently, few or no age constraints exist (Rabassa, 2008).

These and existing data (Hein *et al.*, 2010; 2009; Sylwan *et al.*, 1991) give quantitative evidence of five major advances of the Patagonian Ice Sheet in the Lago Pueyrredón valley since the Early Pleistocene (Fig. 3). The Caracoles limit dated in this study likely correlates with MIS 16, occurring at ca. 620 – 675 ka (Lisiecki and Raymo, 2005), but the error margins prevent resolving this with certainty. MIS 16 was a severe glacial stage globally (top plot) and in Antarctica, cold (middle plot), dusty (bottom plot) and had the lowest atmospheric CO_2 concentrations ever found in an ice core (Luthi *et al.*, 2008). Interestingly, the most extensive advance of the Patagonian Ice Sheet occurred when benthic marine $\delta^{18}O$ values fluctuated to lesser extremes, and indicate lower global ice volumes and a warmer global climate (Shackleton, 1987).

CONCLUSIONS

For the first time, we demonstrate that exposure ages from outwash sediment can be used to determine the age of glacial sequences in the Lago Pueyrredón valley, Argentina, as far back as the Early Pleistocene. ^{10}Be and ^{26}Al surface exposure ages indicate major advances of the Patagonian Ice Sheet occurred at ca. 1.2 Ma and at ca. 600 ka. The former agrees with independent $^{40}Ar/^{39}Ar$ ages that bracket the timing of the Greatest Patagonian Glaciation. The results indicate long-term stability of glacial outwash terraces in the valley and the opportunity for wider applicability of the techniques involved to better constrain Quaternary glacial events here and in other regions.

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FIGURE CAPTIONS

Figure 1. A) Location of Lago Pueyrredón (LP) and Lago Buenos Aires (LBA), North (NPI) and South (SPI) Patagonian Icefields, the approximate extent of the Greatest Patagonian Glaciation (GPG) (Caldenius, 1932), and the location and ages of limiting ^{40}Ar/^{39}Ar age constraints for the GPG (Singer *et al.*, 2004; Ton-That *et al.*, 1999). B) Identified moraine sequences and sample locations in the LP valley (after Caldenius, 1932). Sylwan *et al.* (1991) measured magnetic polarity. Hein *et al.* (2010; 2009) dated the Río Blanco and Hatcher moraines. The Cañadón de Caracoles (Caracoles) moraine system is older than the Hatcher moraines; the outermost ice limit of this sequence is older than 780 ka (Matuyama-Brunhes transition; Singer and Pringle, 1996).

Figure 2. A) ^{10}Be exposure ages and external age constraints for GPG moraines (see Fig. 1a for location and sources). Sample ID listed at bottom. Analytical uncertainties: horizontal end caps; external uncertainties: vertical line. Calculated with the CRONUS-Earth exposure age calculator (v. 2.2; Balco *et al.*, 2008) and Dunai (2001)

scaling model; ages differ by < 6% depending on the choice of alternative scaling models. No correction is applied for rock-surface erosion, snow or topographic shielding. Production rates were increased by 5% to account for an inferred low-pressure anomaly during glacial times (see Data Repository[1]). B) The normalized $^{26}Al/^{10}Be$ ratios plotted against ^{10}Be concentration. Outwash cobbles marked with bold ticks in lower plot. These ratios plot within the predicted range for stable and steadily eroding surfaces (Lal, 1991), suggesting the rocks have not experienced episodic post-depositional shielding.

Figure 3. Age comparison of five dated ice limits in the Lago Pueyrredón valley with a marine benthic $\delta^{18}O$ stack – marine isotope stages are numbered (top plot; Lisiecki and Raymo, 2005), and the Antarctic EPICA Dome C deuterium (middle plot; Jouzel *et al.*, 2007) and dust (bottom plot; Lambert *et al.*, 2008) records.

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[1]GSA Data Repository item 2010xxx, containing sample descriptions and photographs, information on chemistry, age calculations, data tables and further discussions**,** is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure1

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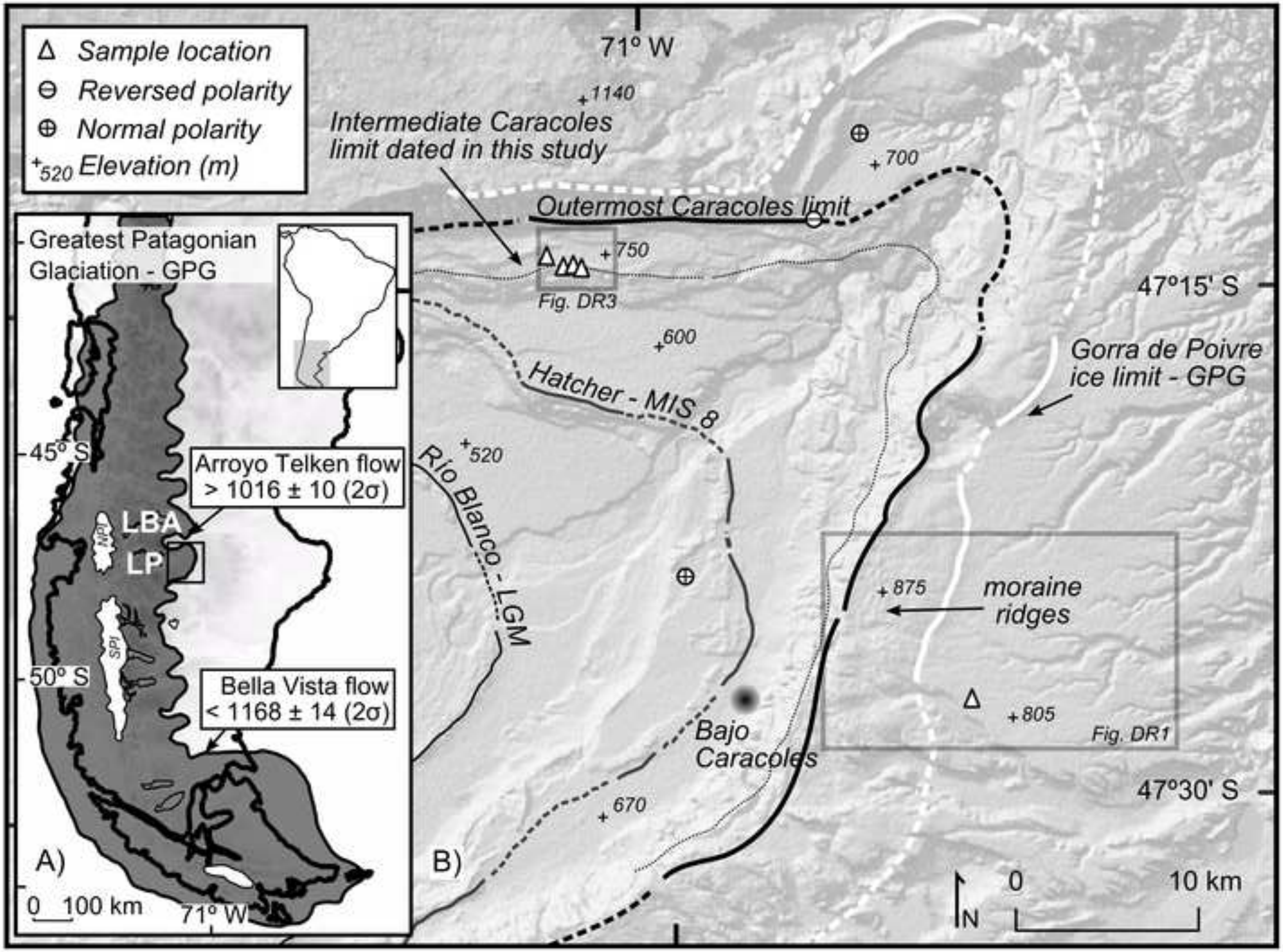

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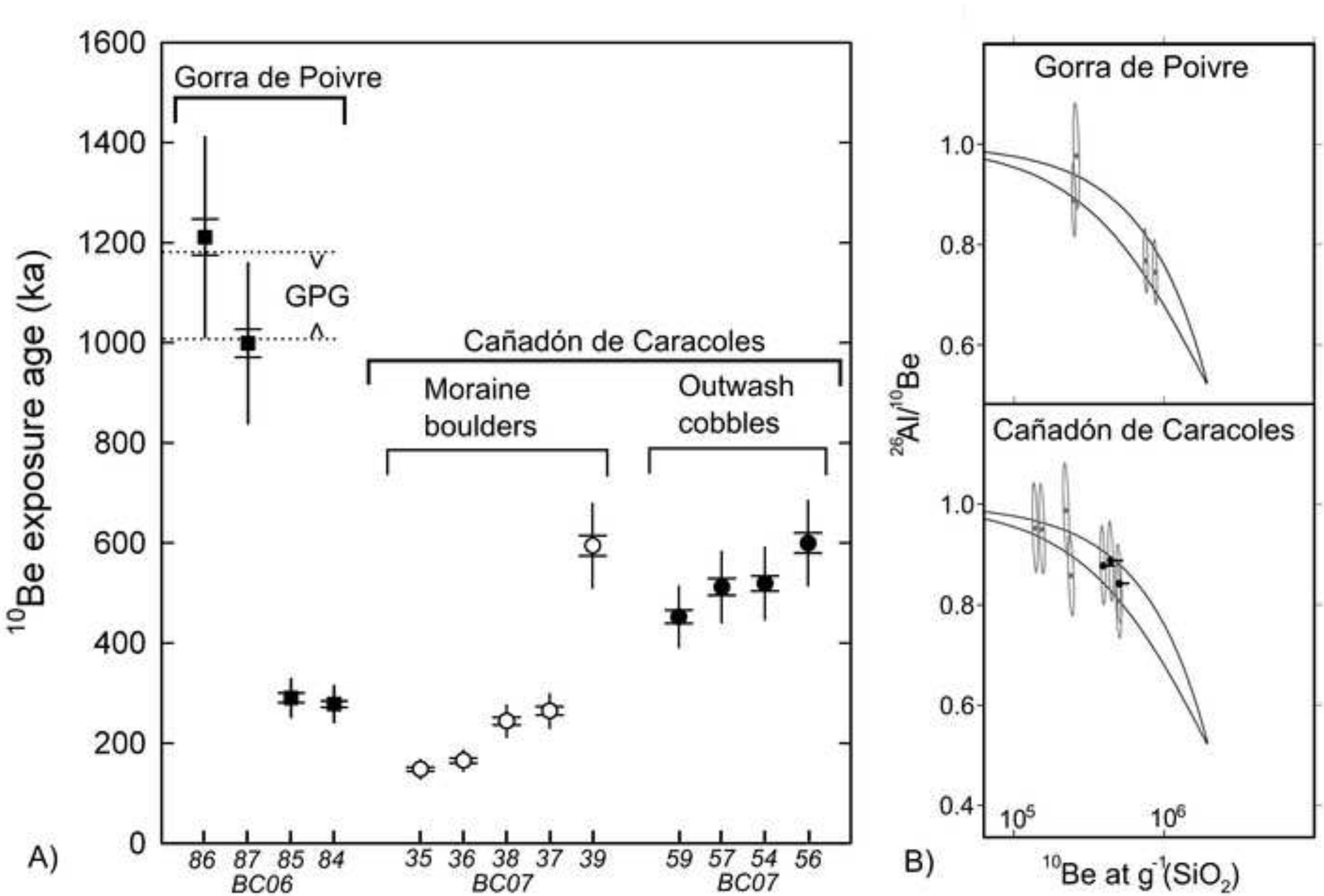

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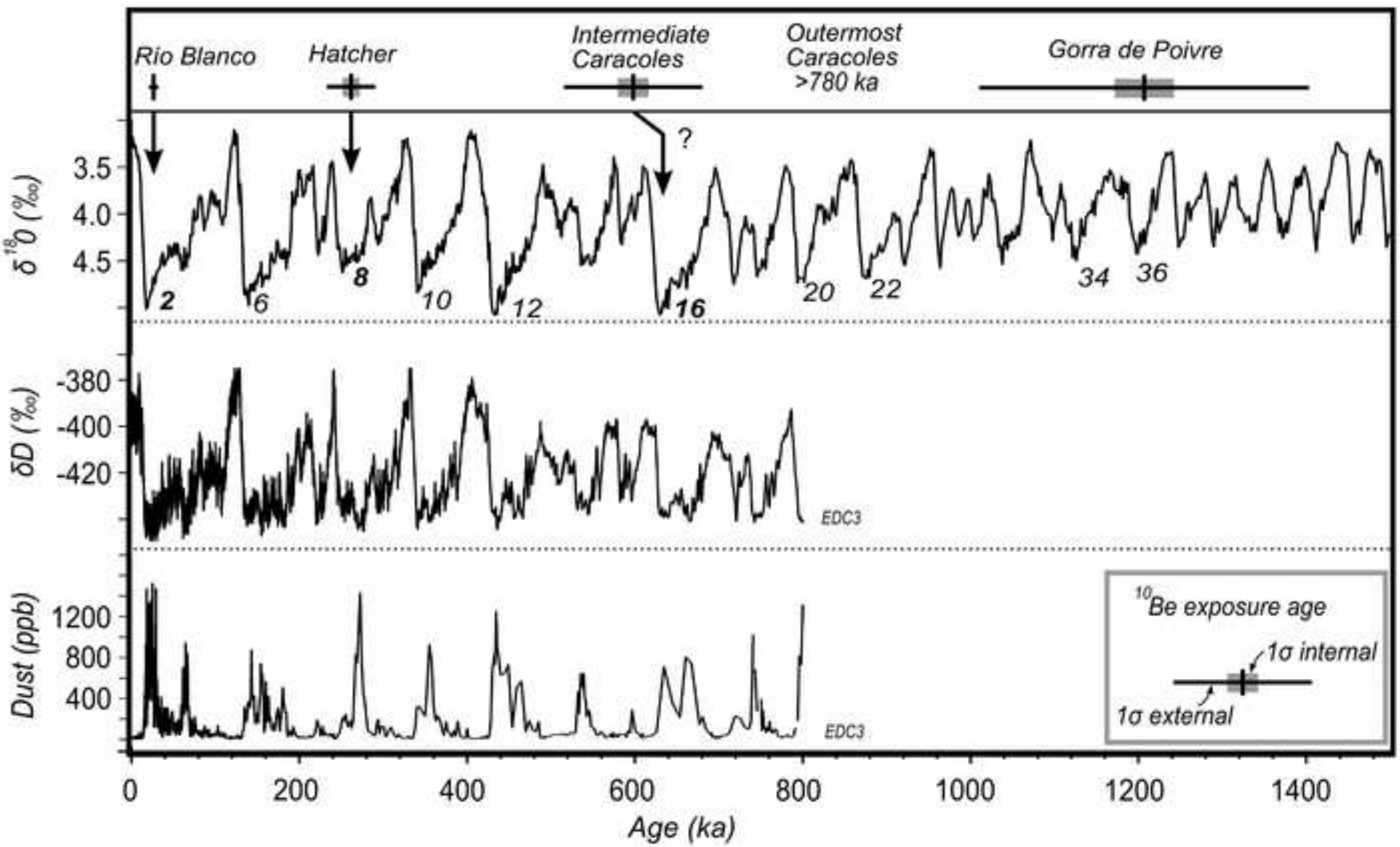

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FigureDR1

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